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The effect of unilateral side flushing on the integrity of the workpiece under different machining conditions

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Abstract

Electrical Discharge Machining (EDM) removes material by melting and vaporization as consequence of high temperatures generated by high-frequency electrical discharges. This result changes the material integrity, due to the production of an affected layer and micro-cracks. In this study, the integrity generated by the use of unilateral side flushing in EDM was evaluated. The experiment consisted of machining square cavities with different parameters. Analysis of texture, roughness, affected layer and micro-hardness were investigated. The results show variations in the thickness of the affected layer at different positions of the machined cavity and showed changes with machining conditions along the flushing path.

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*Keywords:*Electrical Discharge Machining (EDM); Surface analysis; Affected layer

1. Introduction

Electrical discharge machining (EDM) is a nontraditional machining process used to manufacture hard and brittle materials and complex geometries with high accuracy. It is frequently used in mold and die making [1]. The removal of material occurs due to the conversion of electrical energy into thermal energy through a series of discrete electrical discharges between the electrode and workpiece which are immersed in a dielectric fluid [2]. It results in significant surface change, in the form of a recast layer that results in the formation of cracks, high tensile residual stress and a rough morphology [3].

The objective of this paper is to study the impact of machining a hollow cavity by EDM using different roughing parameters and unilateral side flushing. Surface quality, affected layer and micro-hardness were evaluated. All data was subjected to an analysis of variance (ANOVA) with 5% significance.

2. Methodology

All the samples were obtained using an EDM Engemaq machine, model EDM 440 NC. The electrodes used were made of C11000 Electrolytic Tough Pitch (ETP) Copper. The workpiece material was AISI P20 steel, with hardness between 350 and 380 HV. The dielectric fluid was a mineral oil Microcorte 102-A. The workpiece was completely submersed in dielectric fluid, and was flushed with one external nozzle at a pressure of 0.5 MPa. The nozzle opening was rectangular (25 mm x 1 mm), positioned with a 30° inclination from the workpiece surface. Roughing conditions used are given in Tab. 1. An automatic gap and positive polarity was used. The electrode was set for a 2 mm retreat between cycles. A square cavity was open with a copper electrode with 14 mm x 14 mm dimension and 8 mm depth. After that, the cavity was extended using a copper or graphite electrode to a 15 mm x 15 mm hole with 9 mm depth. Four different machining conditions were used. A replica was made for all conditions. Surface characterization was conducted

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through SEM texture image analysis using a MIRA3 TESCAN FEG-SEM. Surface roughness evaluation was conducted using a Mitutoyo SJ-301 surface roughness tester. The parameters analyzed were: arithmetic average roughness (Ra), average peak to valley height (Rz (med)) and maximum height of profile (Rz). The parameters were obtained according to the ISO 4287:1997 standard. The analyzed locations were the flushing entrance wall (EnW), the exit wall (ExW), the bottom side of the flushing entrance (EnB) and the exit (ExB). Six measurements were made.

Table 1. Machining conditions

Condition	Current Density (A)	Off Time (µs)	Erosion Time (s)	Number of cycles before a full retreat
Starter hole	18	100	1	10
Cond. 1 (C1)	12	90	0.5	5
Cond. 2 (C2)	12	90	1	5
Cond. 3 (C3)	12	90	0.5	10
Cond. 4 (C4)	12	90	1	10

The affected layer thickness was measured in four different cavity locations. Six measurements were made in each analyzed spot at 500 times magnification. The samples were etched with Nital 2% solution. The analyzed positions were showed in Fig. 1: the flushing entrance wall, near the workpiece surface (EnW1) and near the cavity bottom (EnW2), and the flushing exit wall, near the workpiece surface (ExW1) and near the cavity bottom (ExW2). Hardness measurements were performed with Vickers microindenter Shimadzu Mitutoyo, using a 0.025kg load, following the ASTM International Designation E384 – 11. The hardness measures were performed 20, 40, 60 and 80 µm from the surface. All roughness, affected layer thickness and hardness data were subjected to an ANOVA analysis with 5% significance.

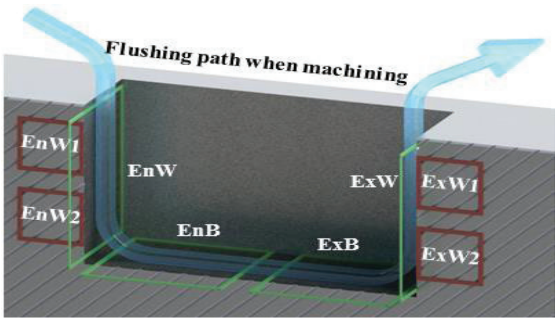

Figure 1. Analyzed spots along flushing path

3. Results and discussion

3.1 Surface Quality

The analyzed surfaces textures are shown in Fig. 2. The surface in the bottom of flushing entrance seems smoother and has less molten material at the crater borders. By comparison, the bottom of flushing exit is rougher. No microcracks were found. Surface machined by EDM seems to have a random pattern structure. The surface high peaks are formed adjacent to the melted valleys [4]. No qualitative differences were found in texture among the tested conditions.

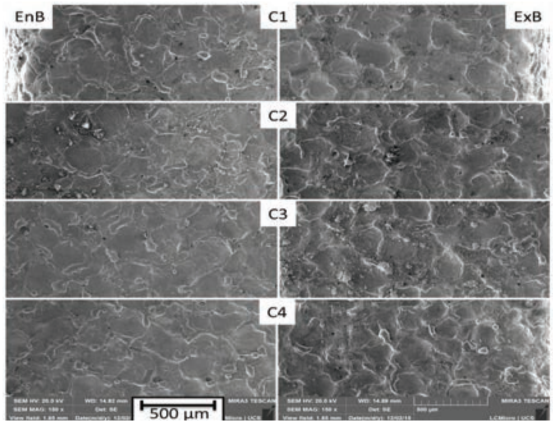

Figure 2. SEM Texture samples. Images of the bottom at the flushing entrance (EnB) and flushing exit ExB for all tested conditions.

Figures 3, 4 and 5 show the behavior of Ra, Rz (med) and Rz , at different analyzed positions within the cavity.

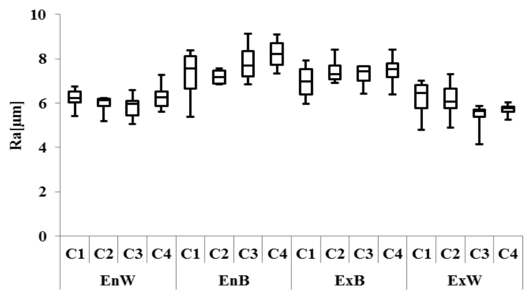

Figure 3. Arithmetic average roughness [Ra]

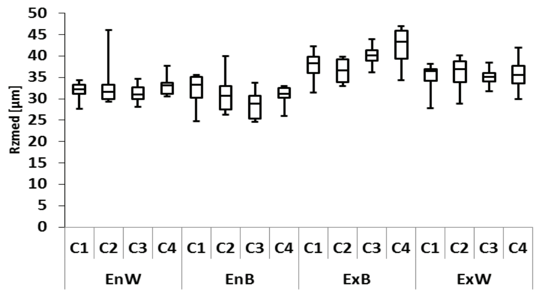

Figure 4. Average peak to valley height [Rz (med)]

The Fig. 3 shows that the Ra is bigger in the bottom than in the wall. In turn the results in figures 4 and 5 show a slight variation in surface roughness in the crater bottom with ExB slightly greater than EnB for Rz (med) and Rz.

The difference in Ra could be caused by the difficulty in remove debris from the bottom and a probable increase in electrode wear, both of them associated with increase of the machining depth. For Rz and Rz (med) the flushing can remove more of the molten material in EnB whereas, in ExB, it changes direction which can hamper molten material removal. This change in the molten material removal may not be sufficient to change Ra, but one time that Rz (med) and Rz are more susceptible to isolated peaks and valleys, it could be affected. Also, the ANOVA (Tab. 2) shows no relevant statistic difference for all the tested parameters.

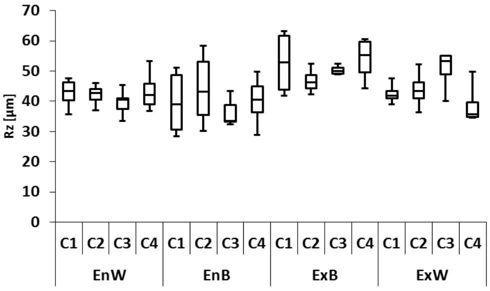

Figure 5. Maximum height of profile [Rz]

Some researchers have found that roughness is affected by the electrode material, but no significant difference was found for different depths, electrode size or when flushing is not used [5]. On the other hand, when machining deep cavities there is a difficulty in removing debris, which can reduce the surface smooth with the machining depth increase [6].

Source of Variation	Ra	Rzmed	Rz
Position in the cavity (A)	0.691	0.815	0.646
Cycles Before a full electrode retreat (B)	0.305	0.478	0.280
Erosion Time (C)	0.969	0.687	0.280
AB	0.233	0.595	0.495
AC	0.782	0.354	0.708
BC	0.418	0.785	0.781
ABC	0.636	0.995	0.334

Table 2. Ra / Rz (med) / Rz ANOVA with 5% significance (P-value).

In terms of surface morphology, the dominant parameters are electrical, in particular the pulse-on duration and pulse current [7-9]. Also the dielectric type has great influence on crater shape [10]. None of these parameters were changed. This, allied with the fact that the gap is occupied by gas bubbles even in immersion flushing [11], can explain why there is no texture and roughness difference between the tested conditions.

3.2 Affected layer depth and micro-hardness

The measurements of heat-affected layer thickness for different cavity spots are presented in Fig 6.

An analysis of different cavity positions shows an uneven affected sub-surface layer thickness. The white layer thickness for EnW1 is potentially smaller in comparison with the other positions for the C1 and C2 conditions. Also the mean for ExW1 appears to be a slightly greater than ExW2 for all conditions. Zeilmann et al. [2] found an uneven affected subsurface layer thickness when machining hollow cavities. A thicker layer was found near the cavity entrance in comparison to the base.

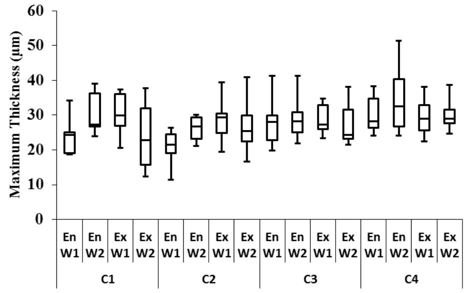

Figure 6. Heat-affected layer thickness

Munz et al. [12] found that the melted material resolidifies along the flushing path. This could explain the difference in the thickness between the positions. A small thickness in the edge near the flushing entrance could occur due the full pressure of the flushing, making the molten material flow along the flushing path. The molten material and the generated debris tend to concentrate in the bottom of the cavity at the flushing entrance wall. The same occurs on the opposite wall, but in the inverse direction. The spot near the bottom tends to present a small thickness when compared to the edge, following the flushing course.

An ANOVA analysis, with a 5% significance was developed. The result is showed in Tab 3. The statistical analysis results indicate a significant difference in the thickness value for (A) and (B). This confirms the graphical analysis. The erosion time by itself did not influence the affected subsurface layer thickness. But, when this parameter is associated to the number of cycles, there is some influence.

Source of Variation	Affected Layer Thickness	Subsurface layer hardness 20 µm
Position in the cavity (A)	**0.009**	**0.000**
Cycles Before a full electrode retreat (B)	**0.003**	0.055
Erosion Time (C)	0.517	**0.032**
AB	0.150	**0.002**
AC	0.722	**0.004**
BC	**0.018**	0.847
ABC	0.240	**0.003**

Table 3. Affected subsurface layer thickness and hardness 20 µm ANOVA analysis with 5% significance (P – Value)

Fig 6 presents the hardness measurements 20 µm above the surface for the conditions tested. From 40 µm to 80 µm, the hardness showed a more homogeneous behavior and for all cavities tends to have a value about 400 HV. For this reason, at the data for the 20 µm location was further analyzed.

The variation in hardness can be explained by diffusion mechanism. The main reason for surface hardening is carbon diffusion into the material structure. Phase changes are a secondary cause of change in hardenable steels [13]. The carbon present in the dielectric fluid can cause a martensite precipitation increase and leads to an increase in hardness [14]. The carbon and hydrogen diffusion is caused by thermal action in EDM process, which can affect the surface and the subsurface hardness [15]. The tendency for a small hardness in the flushing entrance near the edge could be caused by a better flushing condition, it results in better debris remove and cooling of the surface in comparison with other positions. Lower temperature slows the diffusion mechanism. It also explains the elevated hardness in the flushing exit near the bottom. This region is more difficult to flush by the flushing method and this causes an increase in debris concentration and generates less cooling, promoting diffusion. The high hardness found in ExW could be associated to a decrease in fluid pressure along the flushing path. It lowers the heat exchange by convection and hampers the debris removal with results in an increase in diffusion. An ANOVA analysis was conducted on the data in Fig. 7. All influence parameters found are associated with the flushing position, and consequently with the facility or difficulty of occurring the diffusion mechanism. The erosion time is also associated with the same mechanism, since it has a direct influence on the amount of energy transferred to the surface and impacts on the diffusion mechanism.

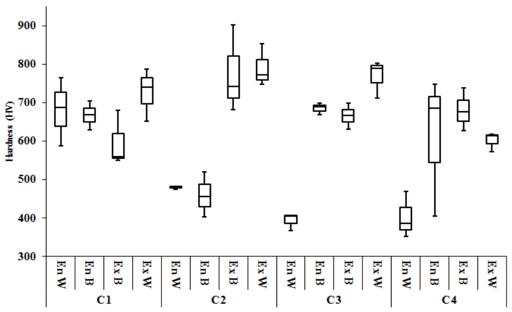

Figure 7. Subsurface hardness at 20µm above surface

4. Conclusion

The investigation of different locations of an EDM machined hollow cavity, with different machining conditions and different locations on the flushing path, has showed an interesting behavior of the surface and subsurface.

- The surface presents a small variation in texture and roughness in the cavity botton and does not depend on proximity to flushing entrance/exit exit. This was probably due to the difficult in flushing away the molten material from the botton near the flushing exit. The ANOVA did not present statistical diference in roughness.
- The ANOVA analysis subsurface layer thickness showed, with 5% significance, an existent difference in the subsurface thickness along the flushing path. The tendency of the recast layer in re-solidified along the flushing path is probably the most influent factor in the subsurface layer thickness difference in a same cavity, for the tested rough EDM parameters and conditions.
- An ANOVA analysis with 5 % significance of the damage subsurface layer thickness difference, considering the number of cycles before a full electrode retreat, showed a great influence of the parameter over the damage subsurface layer thickness subsurface. This is likely associated with flushing difficulty, which impacts the debris concentration and the energy transmitted to the workpiece.
- The erosion time has an influence only when combined with the number of cycles before a full electrode retreat. Alone, the increase of energy transmitted to the workpiece with the increase of erosion time is insignificant, but showed that, when associated with the number of cycle, the increase in energy transmitted to the workpiece cannot be ignored. This information was verified through an ANOVA analysis with 5% significance.
- The position of measurements along the flushing path has a great impact on the subsurface hardness due to the facility or difficulty of heating and debris removal. This affects the difusion of carbon and hydrogen into the workpiece. An improper flushing causes an increase in the subsurface hardness.

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